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Current-driven Vortex Oscillation in Highly Spin-polarized Heusler Alloy Thin Films

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論 文 内 容 要 旨

Chapter 1: Introduction

A magnetic vortex in a sub-micrometer ferromagnetic disk consists of an in-plane curling magnetic moments and a vortex core located at the rotational center in which magnetic moments point perpendicular to the disk plane. Its topologically-stable magnetization configuration and the unique magnetization dynamics have been subjected to much interest from both the physical and practical points of view. In particular, the vortex dynamics driven by a dc spin current was found to be useful for achieving high quality factor ($f_0/\Delta f$; f_0: oscillation frequency, Δf: oscillation linewidth) in spin torque oscillators (STOs) where a self-sustained vortex dynamics is utilized for generating a microwave power. In addition, the application of magnetic tunneling junctions (MTJs) for the vortex STOs has led to a large output power (P_{out}) over 1 μW.

In contrast to the vortex MTJ-STOs, P_{out} larger than 1 nW has never been realized for vortex STOs using all-metallic giant magnetoresistance (GMR) junctions due to their small magnetoresistance ratios (typically < 5%). Despite the disadvantage in P_{out}, the GMR-STOs are still advantageous compared with the MTJ-STOs from the following facts: (i) GMR-STOs are free from the dielectric breakdown which leads to a superior device reliability, (ii) GMR-STOs can operate at a wide range of current density, and thereby can have larger frequency tunabilities, and (iii) GMR-STOs exhibit a negligible shot noise. Moreover, the GMR-STOs are suited for utilizing the dynamics of vertically-coupled vortex pairs which shows peculiar dynamics leading to an extremely high $f_0/\Delta f$.

Then, in this dissertation, we study the vortex dynamics in GMR junctions with Co-based Heusler alloys. Co-based Heusler alloys such as $Co_2(Fe,Mn)Si$ (CFMS) possess high spin polarizations and those enable us to achieve large GMR ratios over 50%. We show that the successful combination of the vortex dynamics and the highly spin-polarized CFMS alloys allows us to realize a large P_{out} over 10 nW as well as a high $f_0/\Delta f$ exceeding 5000. The enhanced P_{out} also enables us to directly address the noises in the GMR-STOs. Finally, we discuss the mechanism of the high-$f_0/\Delta f$ oscillations in the STOs utilizing the coupled vortex dynamics.

Chapter 2: Experimental procedures

Thin films were prepared using an ultrahigh vacuum magnetron sputtering system with a base pressure below 1×10^{-7} Pa. CFMS films were deposited on either Cr- or Cr/Ag-buffered MgO single crystalline substrates at RT and were subsequently in-situ annealed at 500°C to promote the $L2_1$-ordering. Microfabrication was carried out by combining electron-beam lithography, photolithography, ion-beam sputtering and Ar-ion etching.

Chapter 3: Point-contact spin torque oscillators based on $Co_2(Fe,Mn)Si$

It is well known that an electric current flowing in a wire induces a circularly-polarized Oersted field around the wire. This

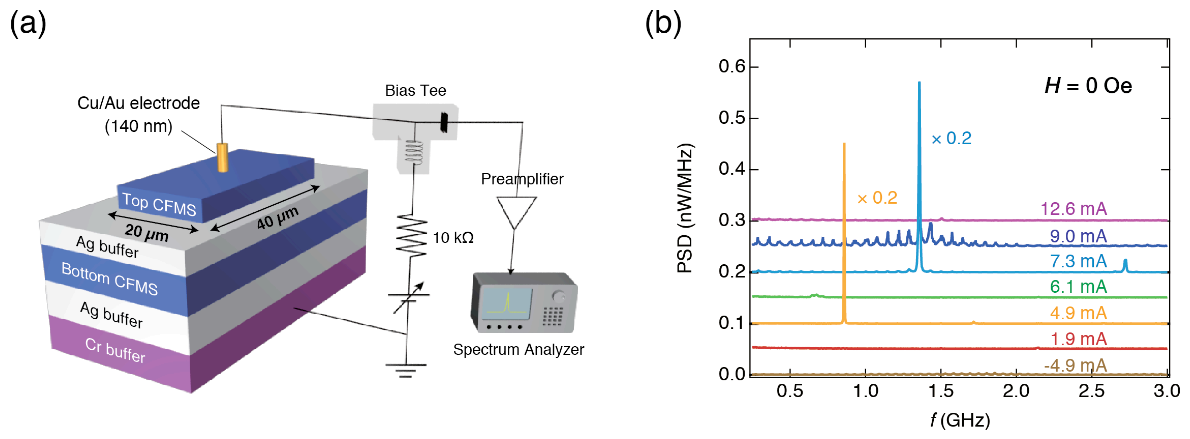

Figure 1: (a) Schematic illustration of the microfabricated device along with the measurement setup. (b) Microwave spectra obtained at $H = 0$ Oe with various I_{dc} values.

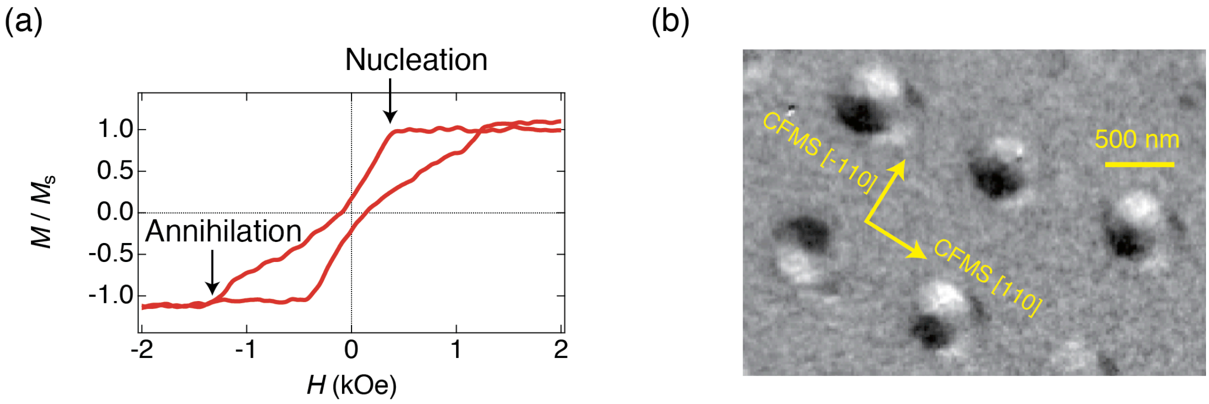

Figure 2: (a) L-MOKE loop measured for a 30-nm-thick CFMS disk array. The nominal disk diameter was 200 nm. (b) PEEM-XMCD image of 50-nm-thick CFMS disks. The nominal disk diameter was 500 nm.

Oersted field can be utilized to form a magnetic vortex in a ferromagnetic thin film. Hence, we first study the oscillation properties of GMR-STOs having a point-contact with a nominal diameter of 140 nm fabricated on a CFMS (20 nm)/Ag (5 nm)/CFMS (5 nm) GMR junction. The injection of dc current (I_{dc}) to the device leads to the nucleation of a magnetic vortex in the 5-nm-thick CFMS layer underneath the point-contact and the excited vortex dynamics can be detected as a time-varying voltage across the junction.

Figure 1(a) schematically illustrates the point-contact STO and the measurement setup. The STO was connected to the measurement circuit via a two-terminal probe and I_{dc} was injected from a source meter from the dc port of a bias tee whereas the microwave signal from the STO was detected by using a spectrum analyzer. Figure 1(b) shows microwave spectra measured without applying external magnetic field ($H = 0$ Oe). In accordance with previous reports, the point-contact STO exhibited coherent oscillations even without applying external magnetic field. More interestingly, although the GMR ratios of the point-contact STOs were considerably smaller than those of nano-pillar GMR-STOs, the devices showed a large P_{out} of 25.7 nW which is even comparable with those reported for nano-pillar GMR STOs. These experimental results demonstrate the advantages of the utilization of magnetic vortex dynamics.

Chapter 4: Magnetic vortices in epitaxially-grown Co_2(Fe,Mn)Si thin films

From the experiments using the point-contact STOs, we found the advantages of vortex dynamics. Then it would be a straightforward idea to stabilize the magnetic vortex to improve the performance of STO. Prior to the fabrication of the vortex STO, we examined the possibility of vortex formation in epitaxially-grown CFMS films at remanence. CFMS films with thicknesses (t) varying from 15 to 50 nm were epitaxially grown on Cr-buffered MgO (001) single crystalline substrates and

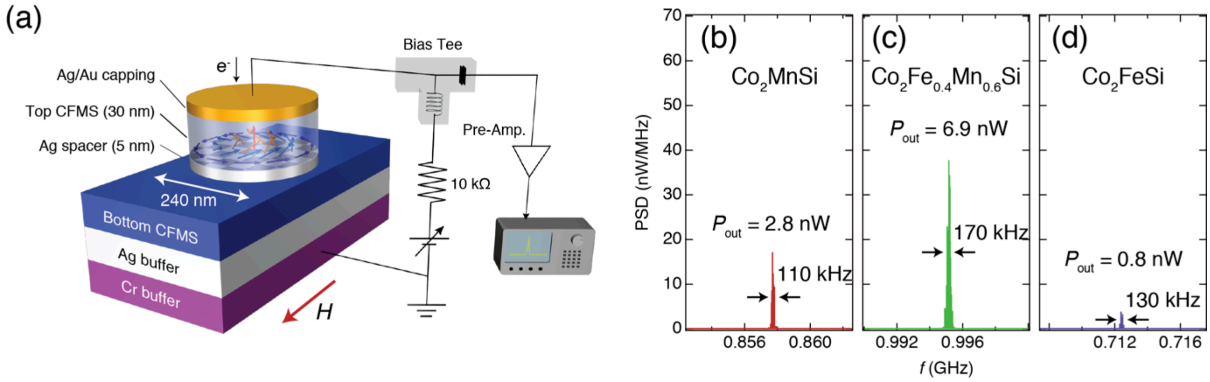

Figure 3: (a) Schematic illustration of a vortex STO along with the measurement setup. (b)-(d) Microwave spectra measured for vortex STOs with various Fe-Mn composition ratios.

were microfabricated into circular disks with diameters (D) varying from 200 nm to 2 µm. The magnetization process and the domain structure at remanence were investigated by using the longitudinal magneto-optical Kerr effect (L-MOKE) and the photoemission electron microscopy with X-ray magnetic circular dichroism (PEEM-XMCD), respectively.

From the L-MOKE measurements we confirmed the nucleation and annihilation of magnetic vortices in the CFMS disks, as shown in Fig. 2(a). Figure 2(b) displays the remanence-state PEEM-XMCD image of CFMS disks with t = 50 nm and D = 2 µm. This image reveals the in-plane curling magnetic moments in the CFMS disks, i.e., the formation of magnetic vortices. Numerical simulations also suggested that the magnetic field at which the vortex was annihilated was rather strongly influenced by the defects formed during epitaxial growth than by the magnetocrystalline anisotropy of CFMS.

Chapter 5: Vortex spin torque oscillators based on Co_2(Fe,Mn)Si

By using the magnetic vortices formed in circular CFMS disks, we developed vortex STOs. Figure 3(a) illustrates the fabricated vortex STO along with the measurement circuit. The devices consist of a GMR stacking structure of CFMS (20 nm)/Ag (5 nm)/CFMS (30 nm) where the 30-nm-thick CFMS layer was formed into a circular disk with a nominal diameter of 240 nm. I_{dc} injected into the device was used to excite the translational motion of the vortex core whereas the time-varying vortex core position led to the microwave emission and was detected by a spectrum analyzer.

Figures 3(b)-(d) show representative microwave spectra measured for the microfabricated STOs with different Fe-Mn composition ratios in CFMS: (b) Co_2MnSi (CMS), (c) $Co_2Fe_{0.4}Mn_{0.6}Si$ and (d) Co_2FeSi. The oscillation linewidths of these STOs were narrower than 200 kHz, yielding a high $f_0/\Delta f$ of over 5,000. The CMS-based vortex STOs also exhibited large P_{out} exceeding 1 nW, and P_{out} was further enhanced by a moderate Fe substitution to Mn for CMS and a maximum of P_{out} = 10.2 nW was obtained for $Co_2Fe_{0.4}Mn_{0.6}Si$. Meanwhile, a minimum threshold current for the oscillation was achieved for the same composition. From an analytical calculation, the radii of the vortex core trajectory were estimated to be ~75% of the actual radii of the CFMS disk, demonstrating the high efficiency of the present STOs.

Chapter 6: Time-domain analysis of current-driven vortex oscillations in Co_2(Fe,Mn)Si

In order to better understand the origin of noises in the CFMS-based vortex STOs, we carried out time-domain measurements and the detailed analyses of spin torque oscillation. We used a digital storage oscilloscope for the time-domain measurements instead of a spectrum analyzer. The large P_{out} of the present vortex STOs allowed us to directly investigate the amplitude noise and the phase noise separately. The experimental results revealed the small amplitude noise of the CFMS-based vortex STOs, which might predominantly originate from the reduced shot noise. The small amplitude noise suppressed the linewidth broadening due to the nonlinear amplitude-phase coupling. We expect that this low-noise property of the CFMS-based vortex STOs would be advantageous for realizing even narrower oscillation linewidth in STOs.

Chapter 7: Coupled vortex dynamics in Co_2(Fe,Mn)Si

Coupled vortices (CVs) are known to exhibit various intriguing phenomena being related to its unique dynamics. In particular,

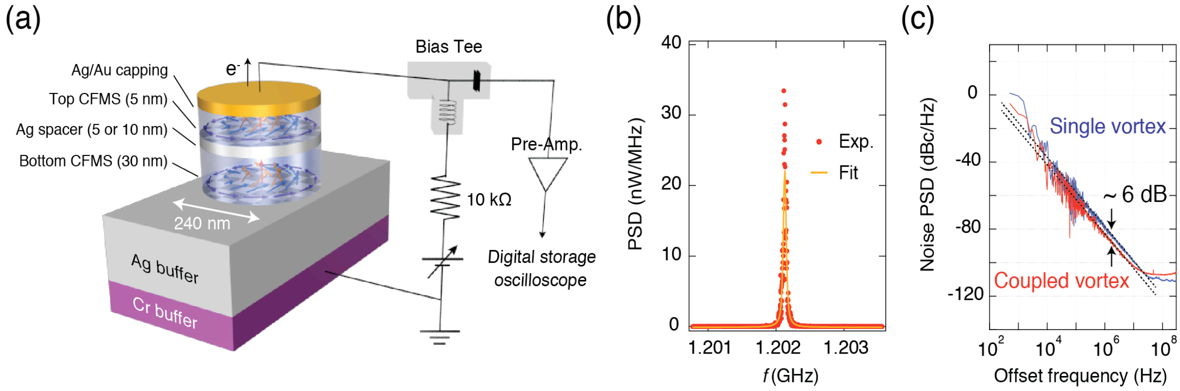

Figure 4: (a) Schematic illustration of a CV-STO along with the measurement setup. (b) Microwave spectra demonstrating $f_0/\Delta f$ of 23,000 obtained from the CV-STO with 10-nm-thick Ag spacer layer. (c) Phase noise spectra obtained from the single vortex STO (blue line) and the CV-STO (red line). Dotted lines are guides to the eyes showing the $1/f^2$ dependence.

the dynamics of vertically-coupled vortex pairs can lead to a high $f_0/\Delta f$ over 10,000 in STOs. The P_{out} of CV-(GMR-)STOs, however, are generally of the order of pW, and that has prevented us from the detailed investigation of the underlying mechanism. Therefore, we developed CV-STOs using CFMS, in which we could expect large P_{out}, and investigated the oscillation properties in detail.

Figure 4(a) schematically illustrates the fabricated CV-STO and the measurement circuit. The CV-STOs consist of a nano-pillar with a nominal diameter of 240 nm made of CFMS (30 nm)/Ag (5 or 10 nm)/CFMS (5 nm) GMR stacks. The difference in the CFMS layer thickness enabled to independently control the polarities of the two vortex cores. The microwave signal from the CV-STOs were detected by using a digital storage oscilloscope.

The CV-STOs demonstrated high-$f_0/\Delta f$ oscillations in a wide range of a perpendicular magnetic field including the zero-magnetic-field. The CV-STO with a 5-nm-thick Ag spacer layer exhibited a maximum P_{out} of 11.2 nW and $f_0/\Delta f$ = 7,900 at the same time, whereas an extremely high-$f_0/\Delta f$ of 23,000 and a relatively large P_{out} of 1.5 nW were achieved for the CV-STO with the 10-nm-thick Ag spacer layer, as displayed in Fig. 4(b). From the noise analysis, we found that the narrow Δf of the CV-STOs originated from the reduction of $1/f^2$ phase noise [Fig. 4(c)]. Furthermore, interestingly, P_{out} of the both CV-STOs showed clear periodic oscillations as a function of the perpendicular magnetic field being associated with the emergence of sideband peaks in the microwave spectra. The oscillation of P_{out} and the high-$f_0/\Delta f$ in the CV-STOs could qualitatively be explained by taking into account the phase-locking effect and the energy dissipation due to commensurate/incommensurate reversal of the vortex core.

Chapter 8: Conclusions

This dissertation was dedicated for developing high performance all-metallic GMR STOs using CFMS Heusler alloys, and for investigating the excited magnetization dynamics. In particular, we focused on magnetic vortex dynamics to realize a high $f_0/\Delta f$ as well as a large P_{out}. The high spin polarization of CFMS and the magnetic vortex dynamics allowed us to achieve large P_{out} > 10 nW and $f_0/\Delta f$ > 5,000 under a small H. The improved P_{out} also enabled us to address the details of the magnetic vortex dynamics excited in the GMR-STOs. The present study clearly demonstrates the advantages of utilizing highly spin-polarized Heusler alloys and the magnetic vortex dynamics, and hence opens up a new route to develop high performance STOs. Since, recently, GMR ratios eve larger than that in the CFMS/Ag/CFMS system have been reported by using other Co-based Heusler alloys and/or other spacer layers, further larger P_{out} would be readily achieved for vortex GMR-STOs.

論文審査結果の要旨

強磁性層 / 非磁性層 / 強磁性層の3層構造に電流を通電させると、伝導電子スピンと局在スピン間に働くスピントルクにより、強磁性層の磁化ダイナミクスを誘起できる。電流による磁化の自励発振現象はスピントルク発振と呼ばれ、ナノサイズの発振器やセンサとしての応用が期待されている。これまでに様々な構造や材料を用いたスピントルク発振素子が提案されているが、発振出力が小さく、発振線幅の制御が不十分であり、電流や磁場による周波数可変の範囲が狭いなどの課題が山積している。加えて、スピントルク発振におけるノイズの機構も明らかにされていない。論文提出者は、上記の課題の解決策として、高いスピン分極を有するCo基ホイスラー合金とボルテックス磁気構造のダイナミクスに着目し、巨大磁気抵抗効果（GMR）素子におけるスピントルク発振現象を研究した。Co基ホイスラー合金の高GMR比とボルテックスダイナミクスの優れた制御性を活用することで、発振の高出力化と高Q値化に成功した。本論文はこの研究成果をまとめたものであり、全編8章からなる。

第1章は序論であり、本研究の背景および目的を述べている。

第2章では、本研究における実験方法について述べている。

第3章では、$Co_2(Fe, Mn)Si$（以下CFMSと略す）層を有するポイントコンタクト型スピントルク発振素子の発振特性について述べている。電流の作るエルステッド磁場を利用することでCFMS層内にボルテックス磁気構造を形成させ、その発振現象を観測した。無磁場下においてもスピントルク発振を励起できること、10 nWを超える発振出力を達成できることなど、重要な知見を得ている。

第4章では、エピタキシャル成長したCFMS薄膜のボルテックス磁気構造について述べている。ディスク状試料の磁化反転過程を系統的に調べ、静的にボルテックス磁気構造が安定化される膜厚とディスク径を明らかにした。

第5章では、第4章で得られた知見をもとに、ボルテックス磁気構造を有するCFMS層から成る膜面垂直通電型（CPP）GMR発振素子の発振特性について述べている。発振特性に対するCFMSの組成依存性を詳細に調べ、ボルテックス磁気構造のダイナミクスに起因した発振現象の観測に成功し、10.2 nWの発振出力が得られた。さらに、スピントルク発振の理論や発振周波数の解析解と比較することで、ボルテックスコアの回転半径を求め、発振の機構について議論している。

第6章では、第5章で開発したボルテックス型スピントルク発振素子のノイズについて述べている。時間領域測定手法を利用することで、CPP-GMRを用いたスピントルク発振素子では、トンネル磁気抵抗効果（TMR）を用いた素子に比べて振幅ノイズを低減できることを明らかにし、線幅制御の観点からボルテックスダイナミクスの改善点を述べている。

第7章では、結合した2つの磁気ボルテックスのスピントルク発振について述べている。結合系を利用することにより23,000に達する高いQ値を得ることに成功した。また、発振出力と線幅の磁場に対する特異な変化を観測し、その機構について議論している。

第8章は結論である。

以上要するに本論文は、高性能スピントルク発振素子の実現に向けてCo基ホイスラー合金とボルテックスダイナミクスの有用性を実験的に示した内容であり、応用上重要な知見が得られていると同時に、磁気構造の安定性、発振ノイズ、結合系の磁化ダイナミクスなどの基礎物理現象の理解に役立つ知見も多く得られ、材料物性学の発展に寄与するところが少なくない。

よって、 本論文は博士(工学)の学位論文として合格と認める。